A SYSTEM MODEL FOR WHITE-TAILED DEER POPULATION MANAGEMENT IN NORTHEASTERN WASHINGTON

By
AKI KATO

A thesis submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

WASHINGTON STATE UNIVERSITY
Program in Environmental Science and Regional Planning

AUGUST 2007

To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of AKI KATO find it satisfactory and recommend that it be accepted.

Chair

ACKNOWLEDGEMENTS

I would first like to thank my committee for their guidance through this project, especially my advisor, Rod Sayler. I would also like to thank those people who had an integral part in the completion of this thesis, including George Hinman and Emmett Fiske for their many hours helping me with suggestions, and Woody Myers for helping me collect data. I would also like to thank Len Zeoli and Allyson Beall for their support with systems dynamic modeling.

A SYSTEM MODEL FOR WHITE-TAILED DEER POPULATION MANAGEMENT IN NORTHEASTERN WASHINGTON

Abstract

By Aki Kato, MS
Washington State University
AUGUST 2007

Chair: Rodney Sayler

White-tailed deer populations, managed by the Washington Department of Fish and Wildlife (WDFW), have increased in northeastern Washington. Reasons for the increase include loss or suppression of historic predators and extensive modifications of original natural ecosystems, which used to influence the size and characteristics of the deer population. WDFW has set as their management goals: (1) keeping the population ratio after the hunting season to 15 bucks to 100 does, and (2) minimizing damage from high deer populations. However, the selection of the sex ratio as a population management metric appears to be without any explicit biological foundation other than having adequate numbers of males for breeding. This project uses system dynamics modeling software (*Vensim)*, to analyze deer population cycles, forage biomass, and hunting influence on sex ratio to show that the critical factor to achieve a stable deer population is not the sex ratio but rather the harvest ratio of does. The model demonstrates the necessity of harvesting at least 20% of does to stabilize the deer herd in northeastern Washington. Even though the model does not include all of the factors that affect deer ecology, WDFW should reconsider the current post-hunting sex ratio target as the essential tool for long-term deer management.

TABLE OF CONTENTS

LIST OF TABLES

List of Figures

1.0 INTRODUCTION

1.1 Human-Deer Conflicts

For thousands of years, white-tailed deer (*Odocoileus virginianus*) lived in the Pacific Northwest with indigenous people and supplied them with clothing and food (Hall 1984). Before the European migration to North America, white-tailed deer occupied the Mississippi River Valley, Texas, Mexico, and Venezuela. Western North America was occupied by mule deer (*Odocoileus hermionus*) (Bauer 1993) and black-tailed deer (*Odocoileus hemionus columbianus*) in a small portion of the west coast. After Europeans settled North America and greatly influenced land use and agriculture, white-tailed deer spread to western areas of the United States. The white-tailed deer is now one of the most common mammals in North America (Hall 1984).

Human activities, such as habitat modification, agricultural development, and predator removal have affected all deer populations (Hall 1984). Their natural habitats have been highly altered and their carnivorous predators have decreased paving the way for population growth.

The explosive growth of a wildlife population is called an irruption, a term first used by Leopold (1943). It leads to populations overshooting habitat carrying capacity and eventual collapse (Ford 1999). In the well-known example of the Kaibab Plateau, the overpopulation of deer caused serious damage to the natural habitat around 1920 (Russo 1964). The deer ate everything within their reach. Local people reported that the vegetation conditions were worse and more deplorable than they had ever seen. The Kaibab deer population started to crash from 1924 to 1928: "75% of the previous year's fawns died during the winter…the deer population fell by around 60% during two successive winters" (Ford 1999, p 183).

Currently, high deer populations are a common phenomenon in North America. One of the primary reasons is that deer have higher reproductive rates than those of other large mammals. Marchinton (2006) explains that, "theoretically, two bucks and four does could produce more than 300 deer in six years without any environmental resistance". Increases in deer population have also been attributed to lack of predators, which historically may have controlled deer populations (Hall 1984).

The modern overabundance of deer has caused many serious problems. McShea (1997, p. 3) has defined several of the features of overabundance: "(1) when the animals threaten human life or livelihoods, (2) when the animals depress the densities of favored species, (3) when the animals are too numerous for their own good, and (4) when their numbers cause ecosystem dysfunction". Currently, all of these situations are occurring in some, even many areas of the United States.

The catastrophic results of over abundant deer have created not only tragic effects on scenery in city parks and gardens but also extreme devastation of natural habitats leading to the death or decline of all plants, insects, birds, and other animals. During the well documented, and now classical, deer irruption in the Kaibab area, vegetation destruction was inevitable, resulting in decreased new and young growth (Binkley 2005). Binkley (2005) also mentions that forests, which usually had many seedlings, had very few from 1929 to 1931. This means complete food chains of this region were affected. Nature, once destroyed, may not recover its original structures easily, if at all, so the effect on natural habitats from overpopulation of deer is a serious issue.

Currently, human-deer conflict from overpopulation of white-tailed deer is occurring in many areas in the United States. The situation has grown especially serious in urban areas, where deer-vehicle collisions (DVCs) and damage to personal property can be costly. According to the Bureau of Wildlife Management, Pennsylvania Game Commission (2003), about 29,000 people were involved in DVCs, and more than 200 people die each year in the United States (Pennsylvania Game Commission, 2003). Nationally, the total annual agricultural cost is five hundred million dollars (Pennsylvania Game Commission, 2003).

On the other hand, deer contribute substantially to the national economy. Hunting licenses and recreational activities, such as wildlife viewing, add a total annual benefit to the United States of over one billion dollars (Pennsylvania Game Commission, 2003). Appropriate strategies for deer population management are therefore required in order to support the economic benefits from deer, yet manage and reduce human-deer conflicts.

Deer management incorporates a number of potential population control measures, such as hunting regulations, sterilization, fencing, predator introduction, and habitat management (Pennsylvania Game Commission, 2003). There is no single perfect deer population management system because each method has its own requirements (Evans, et al. 1999). The lack of methods to accurately count deer populations is another complication (McShea 1997). McShea (1997, p. 5) mentions, "research at the landscape scale is necessary to decide the influence of different deer densities on different populations and ecosystems. Without these data, it is not possible to design appropriate management strategies for given pieces of land". He also explains that it is hard to use accurate population data even if they are available because most of the living components, structures, and functions of the original ecosystems are already lost.

Thus, it is often impossible to manage deer in places where natural ecosystems no longer exist and still animals give them their historical roles in the region. In urban areas, for example, introduction of large predators cannot be used because they are too dangerous to the current human population.

Thus, there are many complex ecological reasons why it is difficult to control white-tailed deer populations. It is important to understand landscape scales, conditions, and management constraints in order to find the most appropriate way to achieve the objectives in each place (Evans, et al. 1999).

1.2 System Dynamic Modeling

"System dynamics modeling" is a practical way to study and experiment with wildlife population management. Ford (1999, p.10) explains, "The "dynamics" in "system dynamics" refers to the fundamental patterns of change such as growth, decay, and oscillations. System dynamics models are constructed to help us understand why these patterns occurs". System dynamic modeling organizes many factors describing a system into a framework that can quickly simulate complicated behavior under the influence of changing conditions.

Several authors have described the uses and advantages of system dynamics modeling. According to Siemer and Otto (2005, p.1), there are "seven stages in building a system dynamic model: problem identification and definition, system conceptualization, model formulation, analysis of model behavior, model evaluation, policy analysis, and model use or implementation". System dynamic modeling can be effectively applied to discussions of complicated problems by utilizing these features. Ford points out that normal thinking about complicated systems often leads to misguided conclusions that reduce chances for correct action (Ford, 1999). Finally

Costanza and Ruth (1998) note that complex systems software has become more essential to assist systems analysts to study system errors, management options, and decision-making.

A system dynamics model has a number of common features. The particular model developed in this project is described in detail but, in common with these models, it uses, in addition to time as a variable: (1) variables that describe quantities, such as the population of male deer, (2) constants that describe the rates of change of these variables with time, and (3) factors that describe the interaction among the variables. To form the model, these quantities are organized into a structure for use in the simulations. Vensim is a versatile commercially-available software package that supports system dynamics modeling. According to Ford (1999, p. 336) "Vensim is visual software to help conceptualize, build, and test system dynamics models…created by Ventana Systems, Inc to support the company's consulting projects for governments and businesses". This is the software package used in this project.

Ford (1999) built a system model that followed a deer irruption cycle and later history from the 1900's in the Kaibab area. He developed animal and plant biomass sectors and used the model to simulate deer populations with predator/prey interrelationships. This model has been changed in this project and expanded to address urban deer management by adding components related to human-deer interactions. This model has two sectors: a deer life cycle sector and a biomass sector. The deer life cycle sector covers birth to death including hunting mortality. The biomass sector, simplified from the models of Ford (1999) and Zeoli (2004), shows how natural forage can affect a deer population. The foundation of my model has been adapted from Zeoli (Len 2004), but factors not relevant to urban deer management have been omitted and factors relevant to management in eastern Washington have been added. According to Ford (1999, p. 11), "a key to the model's usefulness is our ability to leave out the unimportant factors and capture the interactions among the important factors".

Model simulations can test how the two sectors interact with each other by changing parameters in both sectors to show resulting changes in the deer population. Interactions between model elements (factors) are indicated on the program diagrams by arc-shaped arrows. Pairs of such interactions, indicating feedback, are called "causal loops". Two simplified causal loops from the model presented in this report show the relationship between the deer population and standing biomass and between the deer population and hunting activity (Figure 1). In one loop, increasing standing biomass increases the deer population, but increasing the deer population decreases standing biomass; the combination constitutes a feedback loop limiting growth of biomass and deer. In the other loop, deer management practice may dictate that increasing the deer population increases hunting activity, but increasing deer harvest decreases the deer population, another feedback loop limiting population growth. Thus, in this simple example, the deer population life cycle sector and the biomass sector, interact and affect each other. However, the behavior of the model becomes more complicated as the influences of other factors are added. In this report, this kind of system dynamics model is applied to some fundamental deer population problems in northeastern Washington.

2.0 DEER POPULATION IRRUPTION IN THE KAIBAB AREA

In the Kaibab region of north central Arizona, a catastrophic incident of deer population growth occurred in the 1920s. The Rocky Mountain mule deer, commonly referred to as Kaibab deer, had a population irruption and then collapse which destroyed plant communities in the surrounding ecosystems (Russo, 1964).

This area includes long ridges and shallow canyons that have both winter and winter middle elevation range and eventually end on the border of the Kanab Creek drainage (Russo, 1964). There are seven types of vegetation zones: canyon desert shrub, basin sagebrush, short-grass grassland, pinon-juniper woodland, ponderosa pine forest, spruce-fir forest, and mountain grassland parks. This region was originally home to coyotes, bobcats, mountain lions, and wolves (Ford, 1999) and the Rocky Mountain mule deer coexisted with these predators. At the beginning of human occupation of North America, Native American people arrived in the Kaibab region between 475 B.C and 0 A.D. They hunted mammals and gathered nuts or other plants for food. In the 1850's, European people arrived and drove the Native American people away in order to explore this area. The area became a popular hunting site, and the United States government designated the areas as the Grand Canyon Forest Reserve to protect game wildlife, a designation that lasted in the 1900's. At the same time, grazing for livestock had increased by the 1880's, and many carnivorous animals were hunted for human safety concerns. According to Russo (1964, p.125), there was a "total kill of 781 mountain lions, 30 wolves, 4849 coyotes, and 554 bobcats, along with an unknown number of eagle, … on the Kaibab North from 1905 to 1931".

With the absence of predators and hunting by Native Americans, the Kaibab deer herd increased. Russo (1964, p.37) notes that "the deer population in 1906 was estimated at 3,000 to 4,000…but the herd increased to approximately 100,000 herd between 1906 and 1924" (Russo, 1964, p, 37). As a result, the vegetation was eaten, and skirted trees were common. In 1924, starvation hit the deer herd because deer lost most of the available plants they could eat. There were many starving and weak deer, and dead bodies were found everywhere throughout the entire year. The die-off continued up to 1931 (Russo, 1964). The living conditions for deer were miserable, and local people said the environment was like fiction (Russo, 1964).

The population irruption caused the destruction of the surrounding ecosystems of the Kaibab deer. Underwood (1997, p.185) explains the steps of the irruption: "abrupt growth of a deer population is characterized by three phases: (1) initial upsurge and overshoot of carrying capacity, (2) the crash, and (3) the recovery to intermediate density". These phenomena have a serious impact on local plants, wildlife, and structures of ecosystems (McCullough, 1997). Irruptions can occur when the mortality of the species decreases, or the carrying capacity of the species increases (McCullough, 1997). In the Kaibab area, the deer lost their population controls from predators and hunters, so the irruption occurred. This classic example of overpopulation of deer illustrates the ecological damage that may happen to entire ecosystems.

3.0 WHITE-TAILED DEER IN EASTERN WASHINGTON

3.1 Goals and Management of White-tailed deer by the Washington Department of Fish and Wildlife

The Washington Department of Fish and Wildlife (WDFW) attempts to maintain an optimal-size deer population in Washington, especially in northeast Washington, the primary place that deer populations have been increasing in Washington State (Washington Department of Fish and Wildlife, 2005). Their stated population management goal is "maintaining numbers within habitat limitation. Landowner tolerance, a sustained harvest, and non-consumptive deer opportunities are considered within the land base framework. Specific population objectives call for a post-hunt buck: doe ratio of 15: 100. …The desired post-hunt fawn: doe ratio is approximately 40 to 45: 100" (Washington Department of Fish and Wildlife, 2005, p. 2). In northeastern Washington, to prevent overpopulation of deer and the negative effects from overpopulation of deer, the regional managers set their own specific population goals.

"To maintain white-tailed deer numbers at levels compatible with landowner tolerance and urban expansion and providing as much recreational use of the resource for hunting, and aesthetic appreciation as possible. Further objectives are to meet the state guidelines for buck escapement and to maintain healthy buck: doe: fawn ratios while minimizing agricultural damage from deer." (Washington Department of Fish and Wildlife, 2005, p 10).

3.2 Study Areas

The Washington Department of Fish and Wildlife divides Washington state into 6 management regions; Region 1 (Eastern WA), Region 2 (North Central WA), Region 3 (South Central WA), Region 4 (North Puget South WA), Region 5 (Southwest WA), and Region 6 (Coastal WA) (Figure 2). Eastern Washington has a significant white-tailed deer population. The ranges of Region 1 are from Canada to Oregon and from Idaho to the Columbia (Washington Department of Fish and Wildlife, 2005).

WDFW established Population Management Units (PMU) and Game Management Units (GMU) to manage the deer population at smaller scales within Region 1. PMUs are larger scales, and GMUs belong to the PMUs (Washington Department of Fish and Wildlife, 2005). The number of deer management units and areas is listed in Appendix C.

This research project focuses on PMUs 13, 14, and 15, especially the Spokane and Whitman regions, because these places are urban areas that cannot be used for introduction of predators and instead focus on hunting for deer population management.

3.3 Vegetation and Wildlife

In this region, major plant complexes consist of forests, grasslands, shrublands, and wetlands. There are five kinds of forest zones; subalpine fir, grand fir, Douglas fir ponderosa pine, and western juniper. Grasslands are also divided into 3 types: subalpine, mesic, and xeric. An important characteristic of this region is disturbance, and the landscape has been influenced by mammals, insect epidemics, diseases, as well as wind, flooding, and erosion. These disturbances have influenced vegetation succession of this region and produced plant communities that are adapted and tolerant of regional ecological conditions (Daubenmire 1968, 1970).

White-tailed deer eat major trees and shrubs, such as serviceberry (*Amelanchier alnifolia*), sagebrush (*Artemisia tridentata*), deer brush (*Ceanothus integerrimus*), crabapple (*Malus spp*.), bitter cherry (*prunus emarginata*), Douglas-fir (*pseudotsuga menziesii*), bitterbrush (*purshia tridentata*), willow (*Salix spp*.), and western red-cedar (*Thuja plicata*). They also eat forbs, legumes, grasses and other common plants, including alfalfa (Medicago sativa), burnet (Sanguisorba), dandelion (Taraxacum spp.), clover (Trifoliun spp.), wheatgrass (Agropyron spp.), orchard grass (Dactylis glomerata), fescue (Festuca spp.), lichen, and mushrooms and other fungi (Link, 2004).

3.4 Hunting Regulation

Hunting is the only method for deer population management in Region 1. The WDFW has established big game hunting regulations for Washington (Washington Department of Fish and Wildlife, 2006). Specific rules for hunting seasons and species are contained in the hunting regulation, with the ultimate management goal of maintaining certain target ratios of age and sex of white-tailed deer.

WDFW regulates hunting methods, both to protect hunter safety and control the deer harvest (Woody Myer, personal communication, April 24,2007). The firearm season extends for only nine days: October 16-24 for all white-tailed deer and for 12 days from November 8-19 for white-tailed bucks. Statewide, the firearm season contributes a large deer harvest, and the ratios of methods which are used for hunting are 16: 1: 1.7 for modern firearms, muzzleloaders, and archery. In addition, there are special deer permit hunts. Special deer permits are issued when some landowners need to eliminate deer from their properties, or when overpopulation of deer in specific sites is addressed (Woody Myer, personal communication, April 24, 2007).

3.5 Current Deer Management

In Spokane and Whitman County, the deer population is increasing slightly. One of the important environmental factors, severe winters, has been decreasing in recent years. However, in 1996, the size of the deer herd declined because the winter was severe and killed many deer. Other mortality factors for deer include EHD/Bluetongue, EHD (epizootic hemorrhagic disease), drought and hot summers (Washington Department of Fish and Wildlife, 2005). Since 1996 the deer population has not had serious large-scale mortalities, so the population has increased. Some social problems arise from the expanded deer population, including claims for crop and property damage from deer. WDFW tries to manage the deer herd effectively by improving hunting regulations in this region to maintain deer damage within landowner tolerances.

According to the WDFW, average annual harvests reported by hunters from 1996-2004 are 1200 antlered and 340 antlerless deer in PMU 14 and 1500 antlered and 340 antlerless deer in PMU 15 (Washington Department of Fish and Wildlife, 2005). The number of hunters is changing in several regions, but the average annual number of hunters was approximately 2500-3000 in each GMU during 1996-2004 (Washington Department of Fish and Wildlife, 2005). Although the number of hunters decreased in the early 90's after the peak of the 1980's, the number of hunters is currently stable. The WDFW does not have any concerns about the number of hunters to regulate the deer population so far. They do not know the exact number of white-tailed deer in this region because deer, especially bucks, move around, and it is difficult to accurately count the population. Instead, WDFW estimates the deer population by surveys of hunters. They also use sex ratio information derived by the survey for population management. The WDFW specifies target age and sex ratios, and estimated there were 44 bucks: 100 does in pre-hunting season and 16 bucks: 100 does in the post-hunting season in 1999 (Washington Department of Fish and Wildlife 2005). As mentioned, the goal of the WDFW is retaining 15 bucks per 100 does. The WDFW analysis indicates that the white-tailed deer population is not seriously increasing under current management.

An issue with the current WDFW hunting regulations is that they focus heavily on buck hunting compared to hunting does. To keep a static sex ratio of 15 bucks to 100 does, hunters need to kill six times more bucks more than does. This approach also reflects a strong hunter preference for hunting bucks. According to Woody Myers, from WDFW, the goal of the sex ratio was decided without any particular or highly specific scientific justification, so the ratio should be tested whether it is appropriate for their deer population management (Woody Myer, personal communication, April 24, 2007). The population model simulations conducted in this study illustrate the effects on the deer population of varying the sex ratio by hunter harvest. I then draw conclusions about whether the after hunting season harvest sex ratio used by the WDFW for deer management is appropriate for maintaining a relatively stable or non-increasing white-tailed deer population.

4.0 MODELING WHITE-TAILED DEER IN NORTHEASTERN WASHINGTON

4.1 Constructing the Model

Drawing a reference mode is the first step in constructing a system model and will be an ideal transition from an initial to a final state in the system dynamic modeling. The goal of the WDFW is to minimize the damage from the deer population and to keep a stable sex ratio between bucks and does after hunting, specifically at 15:100, so the reference mode will reflect the goal of achieving this sex ratio after hunting with stable population. Figure 3 shows the shape of the sex ratio goal desired by WDFW. In Region 1, the deer population currently is increasing slightly, and the WDFW has plans to manage and improve the population in the area. The modeling results in this section will test whether the sex ratio of 15:100 and an acceptable set of hunting regulations are consistent with the reference mode shape of the population in Figure 3.

Because there is an absence of actual population data for white-tailed deer in eastern Washington, the model in this study estimates and analyzes deer population growth using previous work from deer population models presented by Ford (1999) and Zeoli (2004). In the model in this study, there are two sectors, the deer population life cycle sector and the biomass sector. The deer population life cycle sector shows the cycle of deer birth and mortality. There are three stocks in the model for fawns, bucks, and does. These stocks are connected with inflows and outflows called birth and the factors of their mortality. Figure 4 shows a simple model including just these primary stocks and flows.

This model displays a basic deer life cycle from birth to death. The fawn stock comes originates from birth and goes to two stocks, adult bucks and does through fawn survival. The two adult stocks have two outflows, which are natural death and hunting. The total population is the sum of the populations of fawns, bucks, and does. To calculate birth and mortality, other variables must be added. Figure 5 shows the whole model of the deer life sector, including every selected factor in the model that affects the deer life cycle. For example, deer birth is related to the number of female s and the equivalent fraction of needs met from the forage biomass sector. As additional background information, the following list identifies the source of data used for the modeling:

Washington Department of Fish and Wildlife

Parameters: fawns, bucks, does, new growth within reach of deer, standing biomass within reach of deer.

Halls (1984)

Parameters: sex ratio, fawn survival rate, normal birth rate with needs met.

Zeoli (2004)

Parameters: natural death rate, decay rate, lookup birth rate, lookup productivity multiplier from damage.

Ford (1999)

Parameters: decay rate, lookup productivity multiplier from fullness, total forage required per deer per year.

According to Hall (1984), the average deer birth rate is 0.68 if their nutrition needs are met. Otherwise, the rate decreases. The equation is expressed by normal birth with needs met, equivalent fraction needs met from the biomass sector, and birth rate reduction due to reduced forage. The number of does also influences the birth rate. These factors decide the number of fawns. The average fawn survival rate is 58% until they become mature bucks and does, usually at 1 year (Hall, 1984). The normal sex ratio is 50% each, so the fawn population goes to adult bucks and does through survival rates and sex ratio.

The two stocks, bucks and does, go to two causes of their mortality, which are natural death and death due to hunting. Their natural death is also affected by the equivalent fraction needs met by biomass for forage. If their nutrition needs are met, 10% of them die a year. If not, their mortality will increase as well. The other cause of mortality is hunting. The WDFW focuses on after-hunting sex ratio for their deer population management because they cannot accurately count the number of deer. In the actual running model, both the buck and doe hunting ratio is manipulated via attached sliders (i.e., adjustment bars), so it is possible to see how many deer and how much sex ratio should be killed to obtain the desired sex ratio after hunting. Analyzing these factors provides useful information for the WDFW for methods to improve their hunting policy.

The other sector, the biomass sector, is adapted from Ford (1999), the Kaibab Deer Herd, and from the subsequent derivative model of Zeoli (2004), "An Alterative Explanation for Leopold's Kaibab Deer Herd Irruption of the 1920's". The model in

Ford's textbook demonstrates how the Kaibab deer had a population crash through an absence of predators and hunting by Native American people in the 1920s with two modeling sectors, a prey-predator sector and a biomass sector (Ford 1999). He mentions how the number of deer changed and caused an irruption under situations that did not have an appropriate number of predators in the Kaibab area. In the Zeoli (2004) model, he develops a biomass sector from the Ford model and explains the Kaibab deer story in a different way after adding more biomass factors, historical conditions for deer including hunting by Native American people, and more information on deer predators. Some other factors, which are only important for the Kaibab situation, are eliminated in the model presented in this study.

A key factor in the biomass sector is new and old biomass, which shows how much is available for deer to forage upon, along with the growth rate of the forage biomass. In general, deer prefer new forage, but they start to eat old biomass if new forage is not available because the deer population increases over the rate of the new forage growth. Eating old biomass reduces growth rates of standing forage biomass, and the model can show how the amount of standing biomass changes by the loss of new growth. This model sector has two stocks: standing biomass relevant to deer and damaged standing biomass. As stock flows, it has: additional standing biomass, decay, and foraging on biomass causing damage to standing biomass stock, and dying damaged biomass. Figure 6 displays how these stocks and flows are connected.

The initial standing biomass is 600,000 metric ton (MT), which is double the amount in the Kaibab region because there is a richer plant biomass in the Spokane area. Damaged standing biomass starts from zero. There are many variable converters that show available new and old biomass and how they affect the productivity and growth of biomass. Figure 7 is the complete model of the biomass section.

The biomass cycle starts from the total forage required per deer per year. One deer consumes 1 MT of forage a year according to Ford (1999), so total deer forage required per year is 1 MT multiplied by the number of deer. If new biomass is available, deer eat it. Otherwise, they start to consume old biomass. Old biomass has 25% of the nutrition deer require compared to new biomass, so just eating old biomass affects deer reproduction and mortality if the old biomass is not enough for the total deer population. This converter is called equivalent fraction needs met. Reduction of old biomass also decreases new growth because damaged standing biomass will increase. If the deer population continues to increase, damaged standing biomass also increases. This result means the deer population is growing beyond carrying capacity. Other factors in the biomass section, such as damaged biomass, and fullness fraction affect biological productivity. These parameters are from the Zeoli (2004) model, and they compare supply parts and the demand to the consumption of the deer.

4.2 Simulating the Deer Population Model

These two model sectors are combined to form the full simulation model for a deer population with hunting and forage biomass limits. I will use this model to evaluate the most appropriate hunting policy to manage the deer population in Region 1. A series of graphs show the deer populations each year after hunting the season closes under different hunting scenarios. The final table presented in this report shows the populations when the hunting season begins.

4.2.1 A test for the first model: no hunting

The first test of the model will show what will happen to the white-tailed deer population without any hunting controls on the population (i.e., no predators and no hunting). As mentioned in the introduction, deer have a higher reproductive rate than many other mammals, so they can keep reproducing until they reach their maximum carrying capacity with no controls. Figure 8 shows the result obtained when setting the variable adjustment sliders to all stock and flow converters for these conditions.

The initial populations of bucks and does are different because currently the WDFW hunts 4 or 5 times as many bucks as does, so there are initially more does than bucks (Washington Department of Fish and Wildlife, 2005). As Figure 8 shows, both numbers go up immediately until the buck and doe populations reach about 14,000 and 17,500, where they then collapse. This is exactly the same type of population irruption phenomenon that occurred in the Kaibab area. Figure 8 also shows how the standing biomass declines with the transition of the deer herd. The standing biomass decreases immediately and is replaced by increased damaged standing biomass. Subsequently, the standing biomass, damaged biomass, and new growth are all lost. This means all of the biomass will die leading to the destruction of the entire ecosystem in the area. This example shows that deer population management is essential in current Washington ecosystems, which have already lost their original population regulating factors, especially large carnivorous animals and native vegetation communities and other endemic ecological processes (e.g., fire).

4.2.2 A test for the second model: buck-only hunting

This model scenario shows how bucks-only hunting works for deer management by comparison with no controls. In general, hunters tend to hunt more bucks than does because of trophy hunting. Mature male deer are bigger and have antlers that often are considered to be trophies. According to Hall (1984, p. 232-233), “Trophy bucks are considered those with large, heavy antlers bearing at least four points on either antler”. Hunters derive satisfaction and pride from successful hunts of bucks with these large antlers and hence prefer to hunt for them.

It is obvious that doe hunting can be necessary for deer population management because the number of births depends on the number of does. However, to promote doe hunting, a difficult social or management problem arises considering the difference between hunters preference for bucks and the presumed necessity of hunters for managing stable deer populations. Hunters are absolutely vital to reduce deer populations for deer management programs, but they do not want to hunt does in general. That is why doe hunting is not developed yet in many regions, and I apply this no-doe hunting scenario in this model test. I choose three percentages for buck harvest to show how bucks-only hunting can change the entire deer population, and what the best percentage should be if bucks-only hunting were utilized for deer population management. Figure 9 shows the first modeling result obtained when 10% of bucks are eliminated every year.

As the graph in Figure 9 indicates, the entire deer population will still have an irruption under this scenario. In 5 years, the deer population reaches the maximum, which is about 30,000 total: 12,000 bucks and 18,000 does. Then both populations decline after the irruption, and then the population becomes extinct at 50 years. The only difference in this model compared to the population graph derived with the no-hunting case is that the maximum population is about 1,500 deer lower. This modeling result still has a completely overshooting population shape.

Figure 10 simulates how the deer population changes with a 50% buck harvest and no doe hunting. In this model, the population still has an irruption. The highest number of deer on this graph is about 7,000 bucks and more than 20,000 does at year 5. The maximum number is still close to 30,000 which is similar to the two previous results. The irruption shape of the graph is also the same is in previous results, even though half of the bucks are killed. The next simulation, illustrated in Figure 11, shows the result when all of the bucks are killed, which is not realistic but an extreme situation covered by the modeling. Under this scenario, new males are recruited into the population from the annual crop of fawns. Surprisingly, however, the result is not much different from the previous simulations. From five to seven years, the population peaks at 4,000 bucks and over 20,000 does. Even though the entire population is lower than in past simulations, a population irruption happens again. In the biomass sector, standing biomass shows the same result as the no-hunting case. The entire biomass including standing biomass, damaged biomass, and new growth dies out at the end of the simulation.

These modeling scenarios demonstrate that bucks-only hunting is not an appropriate policy for population management. Deer have a polygamous mating system, so multiple females can get pregnant as long as they have access to one buck according to McCullough (1979). He also mentions “the female segment of the population would continue to grow to equilibrium near K carrying capacity” (McCullough. 1979, p. 144). Eliminating bucks merely decreases the total population, but cannot control birth rates. Of course, buck hunting should be used as part of deer population management because of its effect in reducing the total population and conforming to hunter preferences. Otherwise, buck-only hunting should not be used as the only strategy for deer population management. The focus of management should instead be does, because of their fundamental influence on birth rates. The following graphs show how doe hunting is more appropriate for deer population management.

4.2.3 A test for the third model: doe-only hunting

The previous graphs revealed how buck-only hunting is not appropriate for stabilizing the deer population. In the following model tests, population graphs will show how doe hunting is effective to control the deer herd with three different hunting harvest levels. The first graph, Figure 12, demonstrates the result when 10% of does are harvested.

As the graph indicates, a 10% doe harvest by hunting makes a larger difference in the population compared to buck-only hunting. The total population goes up to 30,000 at 5 to 10 years, and the simulation shows a population irruption. This result is similar to previous models, but the degree of irruption is not as serious as under buck-only hunting because the population is about 10,000 at 50 years. Figure 13 simulates the biomass sector for a 10% doe harvest. Standing biomass still goes to extinction, but the degree is also slower than with no hunting and buck-only hunting. The next simulation will present 20% of does hunting.

Figure 14 illustrates that a 20% doe harvest results in bigger population differences than before. If 20% of does are hunted, at first both populations increase during first 10 years. The buck population goes up immediately to about 16,000, but the doe population stays almost constant at 10,000. The total population reaches a maximum of about 24,000, and then gradually declines. At 30 to 50 years, the entire population stabilizes at around 12,500 bucks and 5,000 does. Figure 16 also shows the biomass sector in this simulation. Standing biomass decreases for 40 years, but then gradually recovers. Damaged standing biomass increases for 25 years and then gradually decreases. New growth decreases at the beginning, but it recovers after 40 years. Thus, doe hunting makes a large difference at the 20% harvest level through control of birth rates. The next graph indicates how the deer population will change under a 30% doe harvest and no buck hunting.

Figure 16 shows a deer population which goes to extinction. The buck population increases to about 16,000 in 10 years but then immediately decreases. The doe population decreases continually from its original number. In this simulation, deer do not have a high enough reproductive rate to keep their population stable. In other words, mortality exceeds birth rates. The reason why the buck population grows at first and then starts to decrease is that there are not enough does to bear fawns at the peak point of the population. Figure 17 shows the alteration of biomass in the 30% does harvest situation. At first, the standing biomass increases because of the intrinsic productivity but shortly thereafter starts to decrease when affected by the short-term increasing population. At 20 years, the standing biomass increases again because the entire deer population is decreasing. This result means that enough standing biomass exists to support the deer population. However, the deer do not have high enough reproductive rates in this model scenario indicating that a 30% doe harvest reduces the deer herd more than necessary. As these simulations show, doe harvesting can contribute to deer population management by changing deer birth rates and recruitment, but it is necessary to carefully determine the best doe harvest percentage to provide this control without initiating overkill of the deer population.

As mentioned in the second model tests, buck-only hunting is not appropriate for deer population management, but buck hunting should be used because of desired adjustments to the entire population and hunter preferences. The simulations described so far show that the current policy of the WDFW (i.e., a post-harvest sex ratio of 15 bucks to 100 does after every hunting season) is not an effective population management strategy because the critical population control measure is doe harvest. If there are 100 bucks to 100 does before each hunting season, and 20% of does are harvested, 88% of bucks should be killed to keep the sex ratio set by the WDFW. However, harvesting 88% of bucks is inappropriate because of the number of hunters, limited hunting seasons, and other potential ethical problems, such as animal-rights issues or public acceptance of high harvest levels. The next deer model simulations will test combining buck and doe harvesting for deer hard management.

4.2.4 A test for the fourth model: combining both bucks and does hunting

As the previous model simulations demonstrate, doe harvesting is much more effective than buck harvesting for deer population management, so the next simulation uses both buck and doe hunting to address the management goals of WDFW as much as possible. Let us set a doe harvest of 22% and no buck hunting, which makes a stable deer population for the long-term as demonstrated from previous simulations. Figure 18 and 19 show these model results, which are almost the same as the result for the case of 20% the doe harvest and no buck hunting. However, in this model, the population does not fluctuate as much as it does for the 20% doe hunting case. The biomass also does not decrease to the 100,000 level and then it also recovers more than in the 20% doe harvest model.

The next model simulations will assess three basic harvest patterns which can be used for deer population management. They simulate the 22% doe harvest which stabilizes deer populations along with three buck harvest ratios: 10%, 22%, and 50%. Figure 20 shows the simulation of harvesting 10% of bucks and 22% of does. The buck population goes up to 12,500 and stays around 11,000. The doe population stays around 9,000 in the first 10 years and gradually decreases to 7,000. This model does not reveal a big difference between buck and doe populations compared to harvesting only 22% of does and no bucks. In the biomass sector, the result is almost the same as in the previous model (Figure 21). Recovering standing biomass is faster than in the previous model because of the lower population size. The sex ratio after the hunting season for this case is about 11 bucks to 7 does, which suggests that hunters could kill more bucks.

The next graph simulates the result for a 22% doe harvest and 22% buck harvest (Figure 22). Both sexes have the same population at 10 years because both sexes have the same hunting ratio. The numbers of both sexes stay around 9,000 after 10 years. In the biomass sector, the result is also the same as in the previous models. Figure 24 analyzes one more case with 22% does harvest and 50% bucks harvest. Both populations remain almost the same with time, 5,000 bucks and 10,000 does. The sex ratio is 1 buck and 2 does, so this ratio is reasonable for deer management problems facing the WDFW. Standing biomass also does not exhibit any serious decrease and approaches 20,000 units with increasing time.

4.3 Discussion

As these system models illustrate, it is essential to consider the sex ratio of the deer harvest for effective deer population management. Buck hunting can adjust the number of bucks and contribute to hunter desires for trophies (Xie, et.al. 1999). Doe hunting can control the number of births and therefore regulate the entire deer population. Xie et al. (1999) aim for both a quantitative goal and qualitative goal in deer management. They explain that current deer population management, which currently uses a high harvest rate of bucks, simply creates high reproductive rates and lowers buck populations. It is important to keep a balanced harvest of both sexes for long-term deer population management (Xie et al. 1999). In fact, many states increase just the number of harvested deer without adjusting harvest sex ratios, but few of them could provide appropriate population management (McCullough 1997). As their models also prove, Xie et al. (1999) conclude that deer populations cannot be stabilized without certain levels of doe harvests. Thus, the WDFW can stabilize the number of births and the population size of white-tailed deer in eastern Washington if strategies of hunting both bucks and does are utilized effectively.

In Region 1, average harvests between 1996 and 2004 were 2700 antlered and 680 antlerless deer (Washington Department of Fish and Wildlife, 2005). Therefore, the harvest of antlered deer is about 4 or 5 times as much as the harvest of antlerless deer. This is not an appropriate sex harvest ratio according to the model simulations in this study. Conseqquently, if the post-harvest sex ratio of 15 bucks to 100 does does not have any specific biological significance, then the doe harvest ratio should be reconsidered for more effective population management. Thus, the establishment of clear and quantitative deer population goals for Region 1 is a necessary first step for long-term deer population management (Evans et al., 1999). Each region has a different social and ecological situation, so WDFW needs to re-examine what deer harvest goals are needed in Region 1. This system dynamics model clearly illustrates how the hunting sex ratio should be changed to stabilize the deer population. However, it is important to note that the WDFW cannot simply use the 22% doe harvesting ratio from this system model, because it does not explain or encompass all of the ecological factors involved in regulating white-tailed deer populations, such as winter severity, summer drought, and diseases.

Even though the WDFW does not know the exact number of deer in this region because it is difficult to census the deer herd size (Washington Department of Fish and Wildlife, 2005), it is possible to estimate the deer population by hunter surveys and analyze the annual increase or decrease of the deer population. As for other methods to estimate the deer population, Evens et al. (1999) suggest that, “indices such as harvest, hunter pressure, pellet counts, browse surveys, and population models are used to measure deer population abundance from year to year”. A critical population variable for management should be the hunting ratio of bucks to does because the number of does can greatly affect the entire deer population.

There are several factors which can be useful in deciding how many bucks should be hunted: the number of hunters, the number of available deer, and the degree of property damage and vehicle collisions attributed to deer. The number of hunters is one of other important factors to consider for the buck harvest ratio, because there will be a limited harvest if there are not enough hunters. Of course, there is a trade-off between the sex harvest ratio and changing annual ecological and social situations. Thus, it is important to collect information and data from hunters and the public to develop appropriate sex harvest ratios every year.

As one apparent example of successful deer population management achieved by hunting regulations, the sex harvest was kept at 1 buck: 1 doe in an attempt to stabilize the deer population in Pennsylvania (Evans et al., 1999). According to the Pennsylvania Game Commission, even if there are some problems with hunter preference, the harvest sex ratio should be set at least at 3 bucks: 1 doe (Evans, et.al. 1999). In Pennsylvania, they succeeded in their deer population management plans by promoting doe hunting. As damage from increasing white-tailed deer populations increases, there will be more doe hunting pressure (Pennsylvania Game Commission, 2003). WDFW is also trying to develop more doe hunting, however, the state population goal is still the same: 15 bucks to 100 does. WDFW needs to encourage more doe hunting to stabilize the deer population by using further public education efforts.

As one of tools for encouraging doe hunting, improving hunting regulations should be effective. Doe hunting is still not popular compared to buck hunting. According to Dalrymple (1973, p. 240), "hunting for bucks is so good few wish to kill a doe. ...All of which illustrates that management in many ways is far ahead of demand, and in this odd instance is often stymied because of lack of demand". While there are special permits to encourage more doe hunting in eastern Washington, the permits are not effective because most hunters do not use them (Washington Department of Fish and Wildlife, 2005). There are also many permits issued for any sex white-tailed deer, but the permits are not usually used for hunting does (Washington Department of Fish and Wildlife, 2005). Thus, it is difficult to use all available hunting permits as currently structured to better regulate the deer population in Washington.

Hunting permits are an effective means, however, to promote doe hunting and their use needs to be improved. For example, if permits for any white-tailed deer do not work to encourage enough doe hunting, the permit should be limited and utilized only for disabled, young, and senior hunters because 71 % of their harvests are does (Washington Department of Fish and Wildlife, 2005). Instead, the WDFW can create other permits for just doe hunting. In another example, special permits issued when landowners ask to decrease the number of deer are getting popular and efficient for deer population management (Washington Department of Fish and Wildlife, 2005). To promote more permits, the landowners should check if hunters kill the appropriate number of does.

Another way to promote doe hunting is by educating hunters of the necessity and benefits of deer population management. In Region 1, the number of hunters is not decreasing, so there are enough hunters so far to minimize damages (Woody Myer, personal communication, April 24, 2007). However, many hunters, especially older hunters, still think that humans should not kill does because they experienced abrupt deer population decreases by over harvesting a long time ago (Woody Myer, personal communication, April 24, 2007). Historically, Americans have thought wildlife belonged to everyone, so people used to kill wildlife relatively unrestricted. As a result, the deer populations decreased significantly, and some people have never forgotten that impression, which is that wildlife can be exterminated more easily and population irruptions are unlikely. Since then, hunting limitations were established, and people tried to kill only bucks in an attempt not to reduce their harvest rates (Woody Myer, personal communication, April 24, 2007). However, the current management situation is completely different, as hunters and other people need to understand what could happen without doe hunting. Thus, for hunters who think that doe hunting should not be allowed and who are interested in buck-only hunting, education should be offered to improve future hunting regulation of deer populations. If hunters have more information, data, and knowledge about what they are doing and how they can contribute to deer population management, this new information can make the hunting experience more interesting (Dalrymple, 1973).

To move closer to more effective deer population management, it is essential to cooperate with the public, and various interest groups and organizations (Riley et al., 2003). Cypher et al. (1998, p.26) mentions how to succeed in making closer relationships with the public to effect a deer population reduction.

"Good public relations and sound biological data are important to the success of any deer-reduction program conducted where public opposition to such an effort is likely to be significant. This opposition may be quite intense and could range from protest letters and demonstrations to legal action and physical interference. Such opposition is likely to come from animal-rights and animal-welfare groups and from citizen groups concerned for public safety…A public meeting should be considered to provide an opportunity for Refuge staff to explain the reduction program and for the public to express concerns and ask questions regarding the program."

These communications can encourage closer relationships with an entire community and promote more efficient management programs to meet everyone's needs (O'Leary and Bingham, 2003).

4.4 Suggestions To Improve the Model

Even though the previous simulations criticize the current approach to deer management in eastern Washington and show that it does not effectively reduce population size and minimize damage from deer, the WDFW reports that the deer population is stable or slightly increasing. The reason for this discrepancy is because this system model does not include other factors that affect deer mortalities, such as winter severity, summer drought, and common diseases. As suggestions for further improvements in deer population modeling, these two main factors of weather and disease can be added in this model.

This model does not include temperature and vegetation differences between summer and winter. The effects of severe winter weather cause significant mortality to white-tailed deer, especially starvation (McCullough, 1979). Deer experience starvation in late winter and early spring when they lose their stored fat. Fawns have more serious starvation and mortality than adult deer. Starvation also causes disease from stress (McCullough, 1979). These influences from winter cause serious population decreases for deer. According to the WDFW, however, recent severe winter weather is declining because of global warming. This warmer climate might actually contribute to an overpopulation of deer. Even though the warmer winter occurs, adding this factor to the model may still influence deer mortality and produce a more realistic model.

The second suggestion for factors that could be added to the model is damage from overpopulation of deer to human properties, such as gardens, fields, crops, and accidents. In Region 1, people lose their crops, fruits, and vegetation in gardens by overabundant deer (Washington Department of Fish and Wildlife, 2005). These kinds of foods are attractive to deer, so landowners will keep losing their products as long as the overpopulation of deer occurs. These total losses could be added in this model to estimate how many people experience damage from deer and receive compensation for it. Deer-vehicle collisions also could be added to calculate the total costs people pay for accidents and add that factor to the model. In this way, WDFW can determine how many deer they need to eliminate and how they can improve their population management of white-tailed deer in Washington.

LITERATURE CITED

Bailey, R. 2001. North America's most dangerous mammal. Retrieved March 5, 2007, from Reason Online Web site: http://www.reason.com/news/show/34914.html

Bauer, E. A. 1993. Whitetails: Behavior, ecology, conservation. St. Paul, Minnesota: Voyageur Press.

Binkley, D. 2006. Was Also Leopold Right about the Kaibab Deer Herd? Ecosystems. *9*:227-241.

Pennsylvania Game Commission. 2003. Population management plan for white-tailed deer in Pennsylvania. Retrieved November 10, 2006, Bureau of Wildlife Management Web site: http://www.pgc.state.pa.us/pgc/lib/pgc/deer/pdf/Management__Plan6-03.pdf

Costanza, R. and M. Ruth. 1998. Using dynamic modeling to scope environmental problems and build consensus. *Environmental Management* 22:183-195.

Cypher, B.L, and E.A. Cypher. 1988. Ecology and management of white-tailed deer in northeastern coastal habitats: a synthesis of the literature pertinent to national wildlife refuges from Maine to Virginia. U.S. Fish Wildlife Service, Biological Report. 88(38). 52pp.

Dalrymple, B. 1973. *The complete book of deer hunting*. New York: Winchester Press.

Daubenmire, R. 1968. Forest vegetation of eastern Washington and northern Idaho. Tech. Bull. 60. Washington Agricultural Experiment Station. Pullman, WA.

Daubenmire, R. 1970. Steppe vegetation of Washington. Tech. Bull. 62. Washington Agricultural Experiment Station. Pullman, WA.

Evans, J., Grafton, W., and McConnell, T. 1999. Deer and agriculture in West Virginia. West Virginia University. Retrieved November 30, 2006, from Fundamentals of deer management Web site: http://www.wvu.edu/~agexten/wildlife/deer806.pdf

Ford, A. 1999. *Modeling the environment*. Washington, D.C.: Island Press.

Halls, L. 1984. *White-tailed deer*. Pennsylvania: Stackpole Books.

Kitching, R. L. 1983. *System ecology: An introduction to ecological modeling*. Saint Lucia: University of Queenland Press.

Leopold, A. 1943. Deer irruption. Transactions of the Wisconsin Academy of Science, Arts and Letters 35:251-369.

Link, R. 2004. *Living with wildlife in the pacific northwest*. Washington : University of Washington press.

Marchinton, L. White-Tailed Deer Biology and Population Dynamics. Retrieved November 30, 2006, from Deer management in Maryland Web site: http://www.arec.umd.edu/policycenter/Deer-Management-in-Maryland/marchinton.htm

Maser, C. 1998. *Mammals of the Pacific Northwest*. Oregon: Oregon State University Press.

McCullough, D. 1997. Irruptive behavior in ungulates. *In*: W.J. McShea, H.B. Underwood, and J.H. Rappole (eds.), *Science of overabundance*. Pp. 69-98. Smithsonian Institution Press, Washington..

McCullough, D. 1979. *The george reserve deer herd*. The University of Michigan.

McShea, W., Underwood, H., and Rappole, J. (eds). 1997. *The science of overabundance*. Smithsonian Institution Press. Washington and London.

Myer, W. Washington Department of Fish and Wildlife. Personal communication. April 24,2007

O'Leary, R., & Bingham, L. 2003. *The promise and performance of environmental conflict resolution*.Washington, DC: Resources for the Future.

Pennsylvania State Forest. 2003. Pennsylvania state forest deer management: a plan for the department of conservation and natural resources. Retrieved Oct 16, 2006, Web site http://www.dcnr.state.pa.us/forestry/deer/Deer_Management_Plan.pdf

Riley, S., Decker, D., Enck, J., Curtis, P., & Lauber, B. 2003. Deer populations up, hunter populations down: implications of interdependence of deer and hunter population dynamics on management. Ecoscience. 10:455-461.

Russo, J. 1964. *The kaibab north deer herd: its history problems and management*. State of Arizona Game and Fish Department. Phoenix, Arizona.

Sajna, M. 1990. *Buck fever*. The University of Pittsburgh. Pittsburgh.

Siemer, W.F. and Otto, P. 2005. A group model-building intervention to support wildlife management. Paper submitted to the 23rd International Conference of the System Dynamics Society

Washington Department of Fish and Wildlife. 2005. Regional Offices. Retrieved 25 June 2007, Web site: http://wdfw.wa.gov/reg/regions.htm.

Washington Department of Fish and Wildlife. 2006. State of Washington: big game hunting seasons and rules. 2006 pamphlet edition.

Xie, J., Winterstein, H., Campa, H., Doepker, R., Deelen, T., & Liu, J. 1999. White-tailed deer management options model (Deer MOM): design, quantification, and application. Ecological Modeling. 124:121-130.

Zeoli, L. 2004. *An alternative explanation for leopold's kaibab deer herd irruption of the 1920's*. M.S. thesis. Washington State University. Pullman, WA.

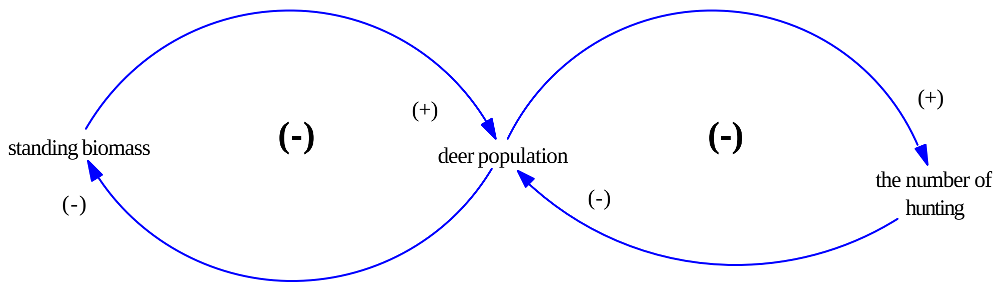


Figure 1. Simplified casual loops of relationships among white-tailed deer populations, standing biomass, and hunting activity. These two loops keep balances between opposing forces, deer population and standing biomass, and deer population and hunting.

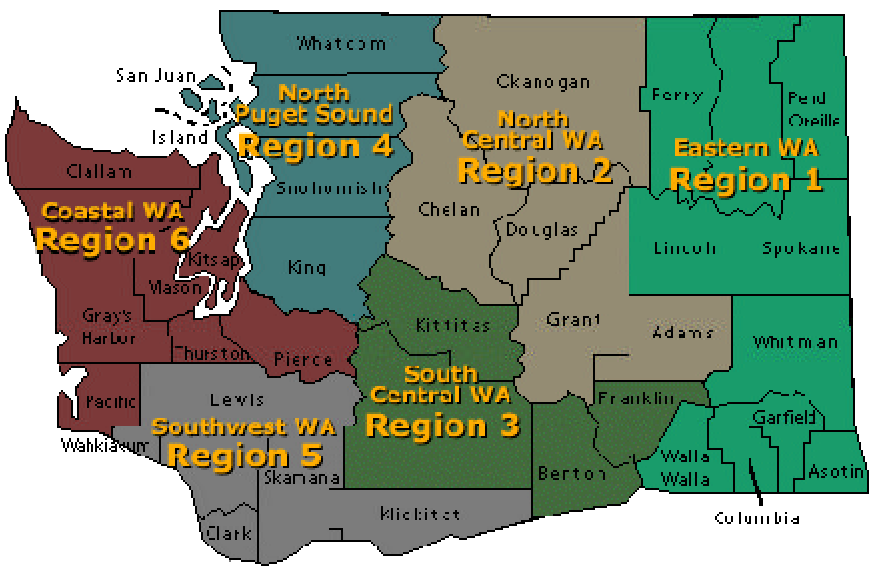


Figure.2 Six deer management regions identified by WDFW. Region 1, which is the focus of the model, is located on northeastern Washington

Figure 3. Reference mode (baseline) for the white-tailed deer population model. This graph represents the goal of the WDFW to maintain a ratio of 15 bucks to 100 does after hunting

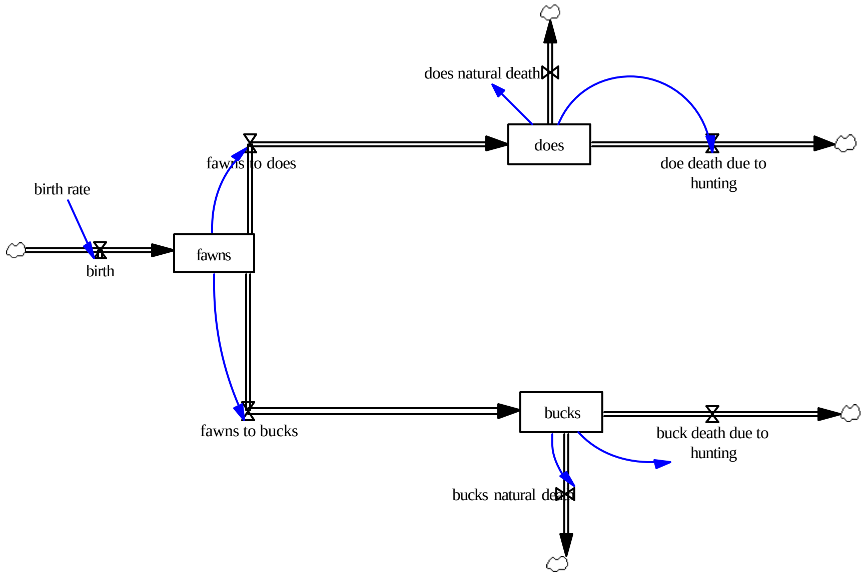


Figure 4. Simplified system model of the deer population life cycle sector. Stocks are square boxes, and flows are arrows connecting stocks. Fawns are born and become adult bucks and does. Adult deer die by natural death or hunting

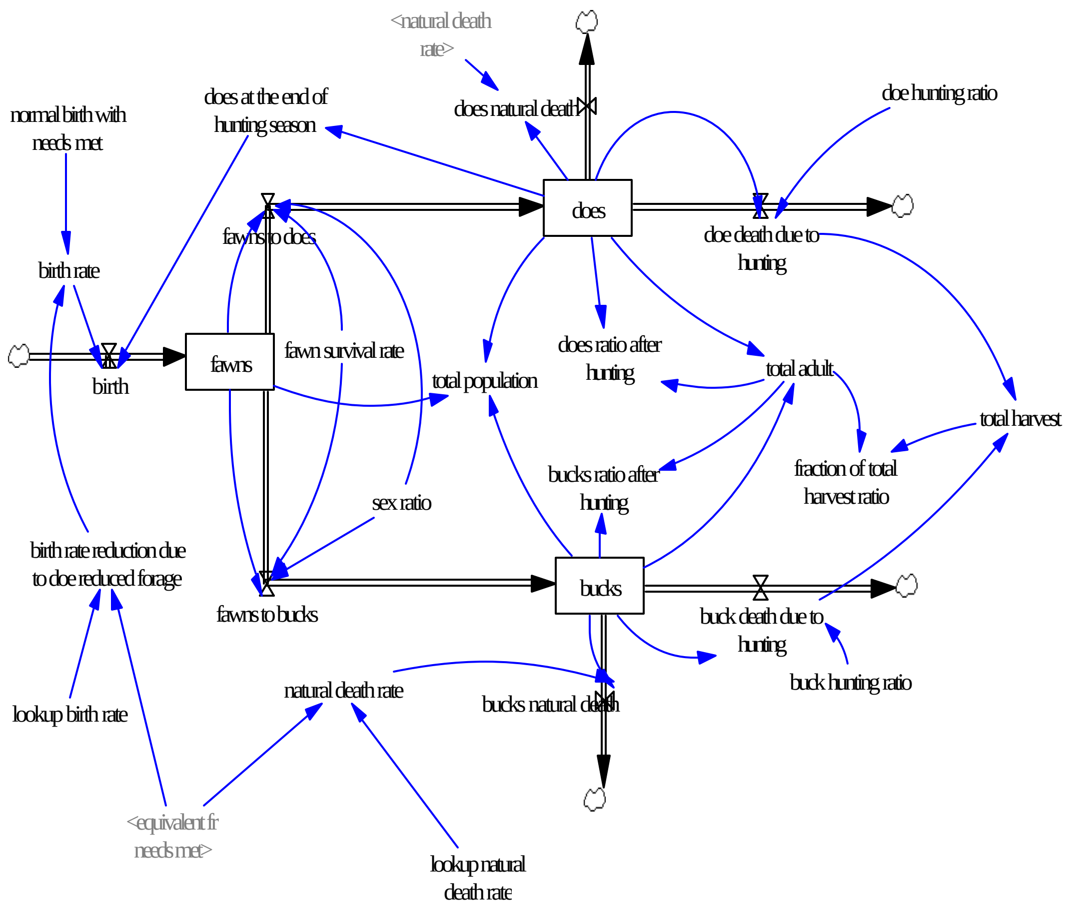


Figure 5. Complete deer population life cycle sector. Stocks and flows are the same as in Figure 4. Converters, represented by arc-shaped arrows, show factors influencing stocks and flow rates.

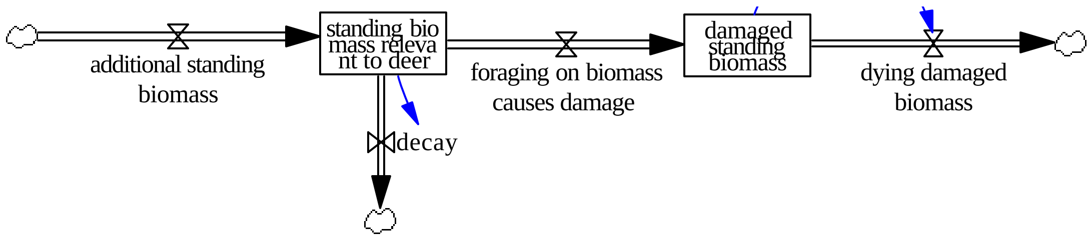


Figure 6. Simplified system model of the forage biomass sector. A source term creates standing biomass, which either eventually decays or is converted to damaged standing biomass by deer browsing.

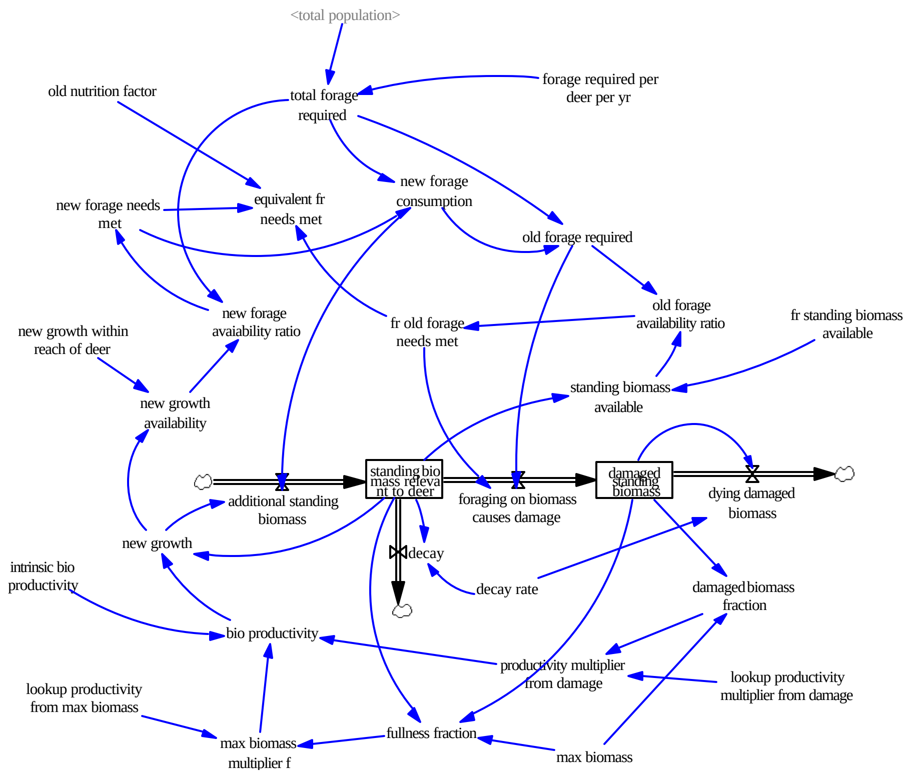


Figure 7. Diagram of the complete standing forage biomass sector in the white-tailed deer system dynamic model

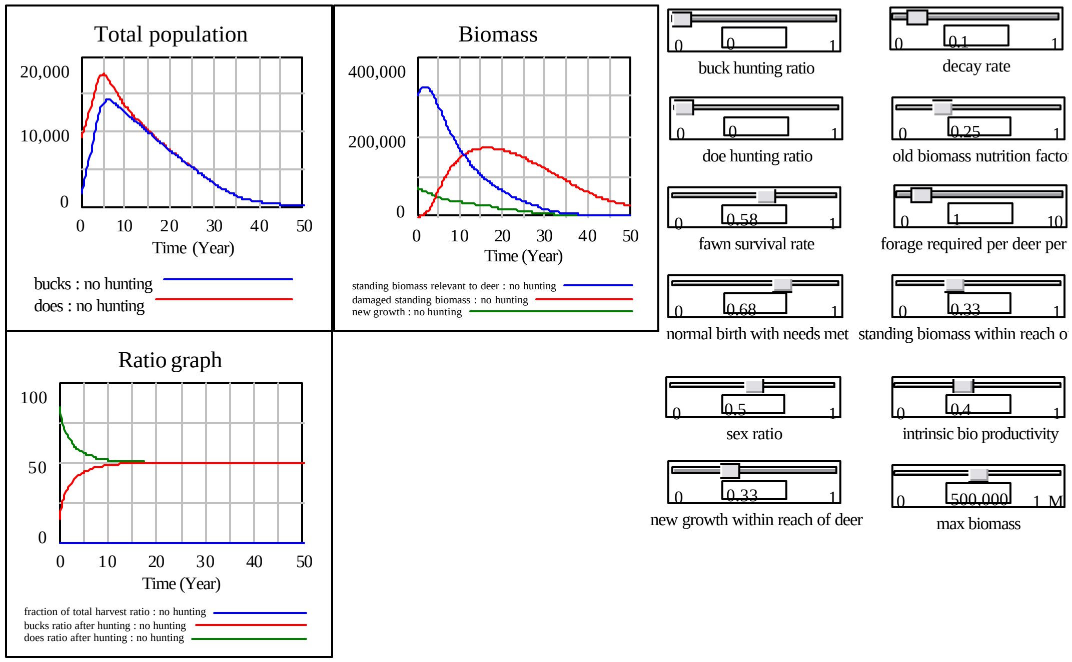


Figure 8. A 50-year simulation of white-tailed deer population response in northeastern Washington under a baseline no-hunting simulation of the system dynamic model.

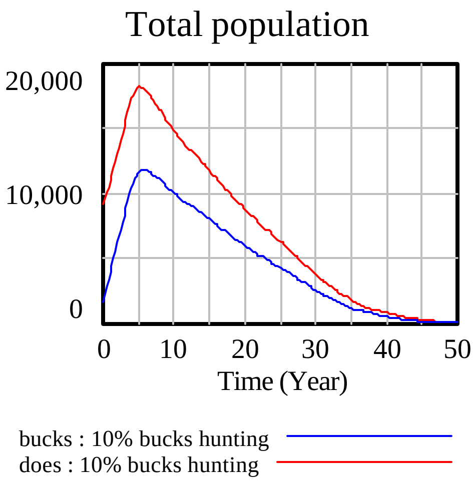


Figure 9. A 50-year simulation of a white-tailed deer population with a 10% buck harvest and no doe hunting.

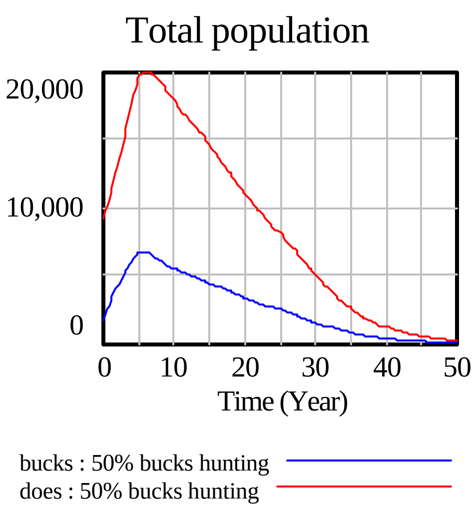
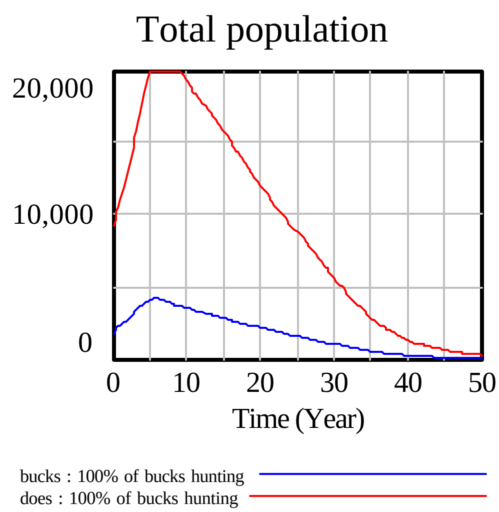


Figure 10. A 50-year simulation of a white-tailed deer population with a 50% buck harvest and no doe hunting.



.

Figure 11. A 50-year simulation of a deer population with a 100% buck harvest and no doe hunting.

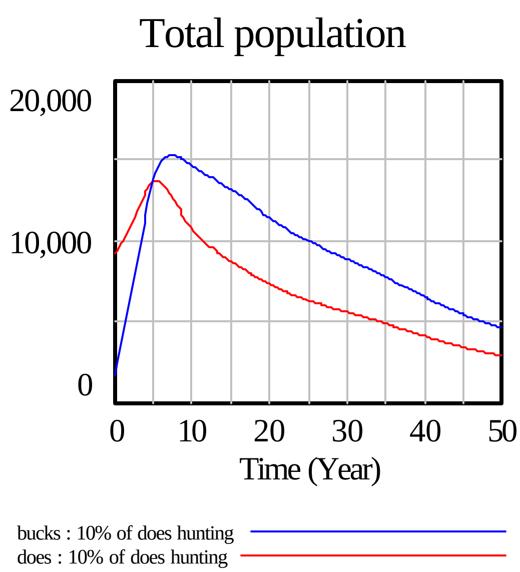


Figure 12. A 50-year simulation of a deer population with a 10% doe harvest and no buck hunting.

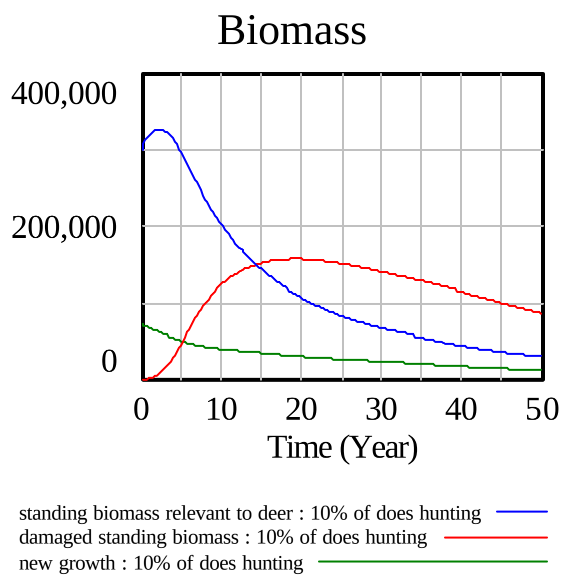


Figure 13. A 50-year forage biomass simulation with a 10% doe harvest and no buck hunting.

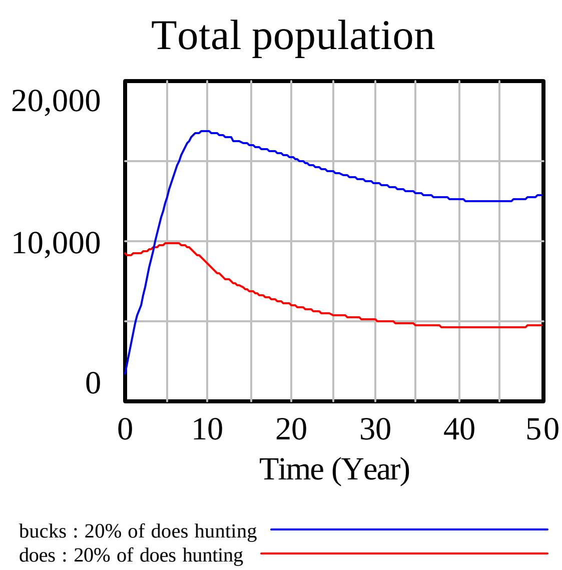


Figure 14. A 50-year deer population simulation with a 20% doe harvest and no buck hunting.

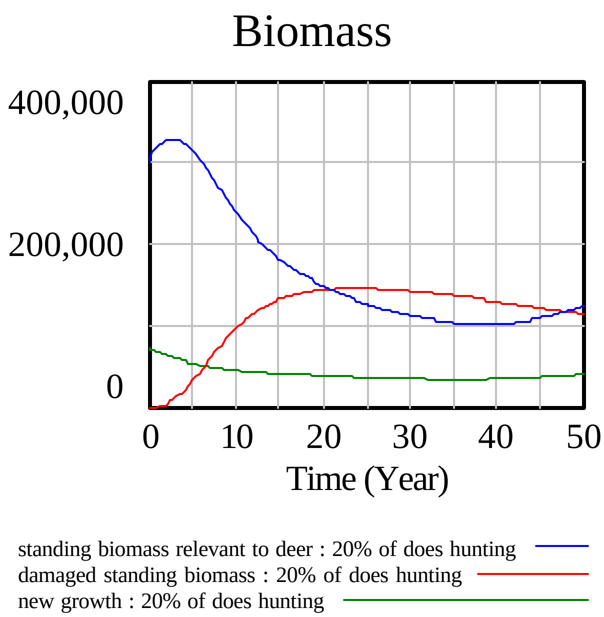


Figure 15. A 50-year forage biomass simulation with a 20% doe harvest and no buck hunting.

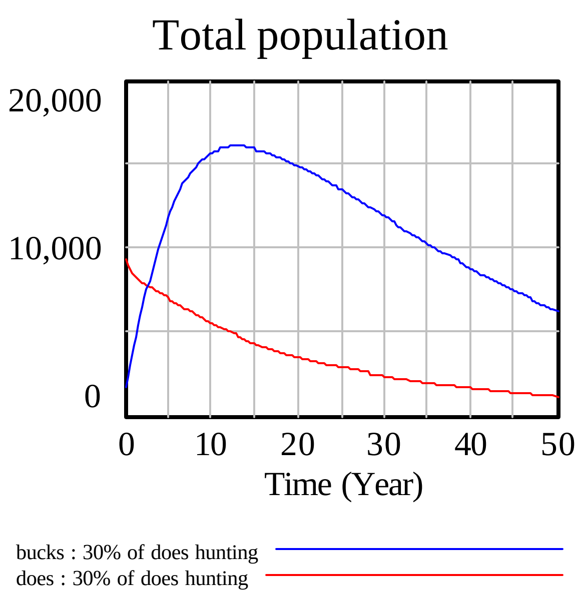


Figure 16. A 50-year deer population simulation with a 30% doe harvest and no buck hunting.

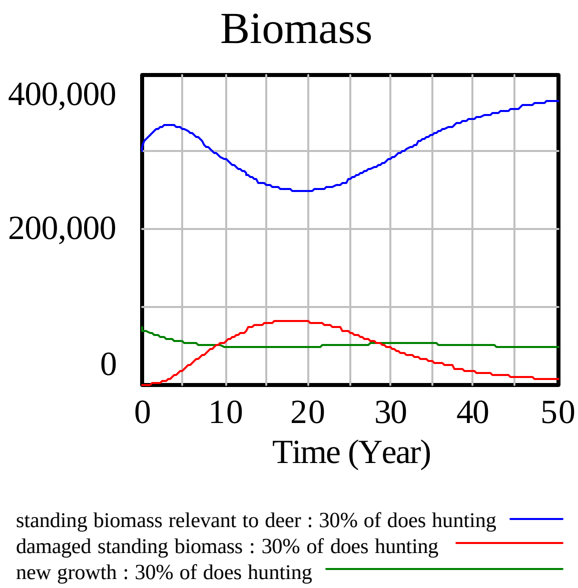


Figure 17. A 50-year forage biomass simulation with a 30% doe harvest and no buck hunting.

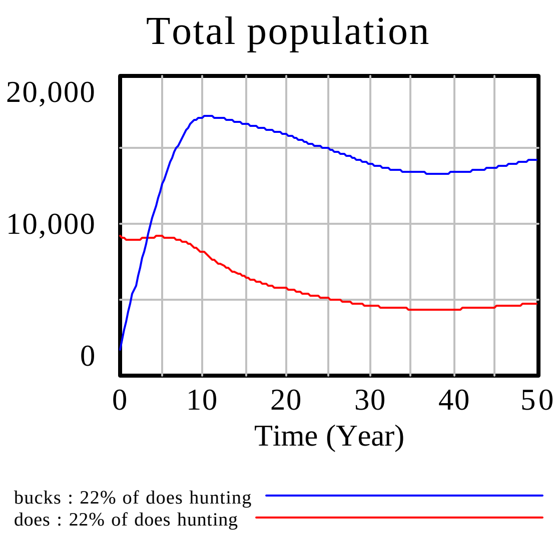


Figure 18. A 50-year deer population simulation with a 22% doe harvest and no buck hunting.

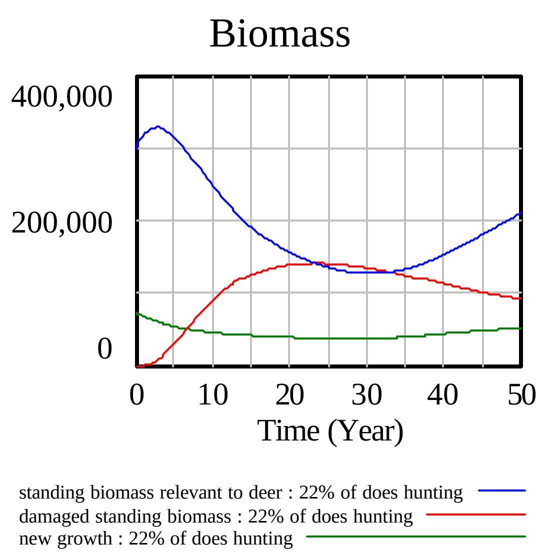


Figure 19. A 50-year forage biomass simulation with a 22% doe harvestand no buck hunting.

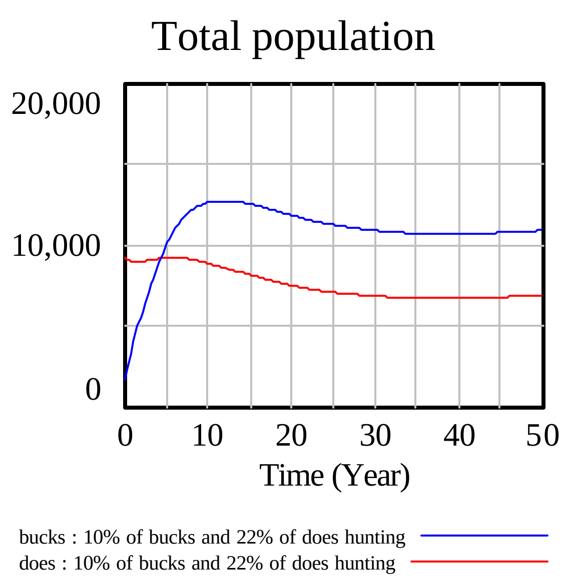


Figure 20. A 50-year deer population simulation with a 10% buck harvest and 22% doe harvest.

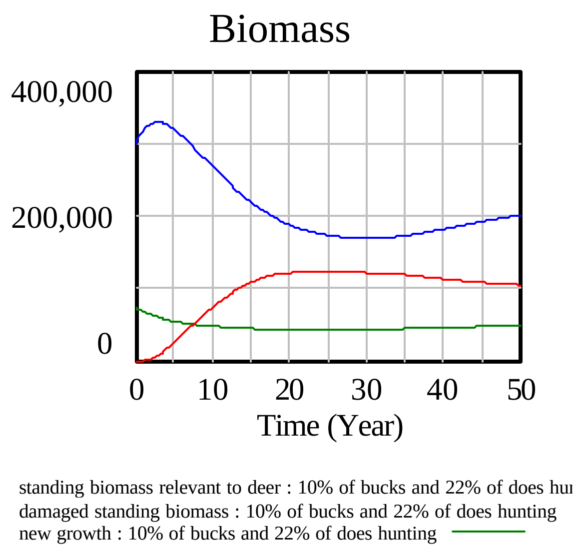


Figure 21. A 50-year forage biomass simulation with a 10% buck harvest and 22% does harvest.

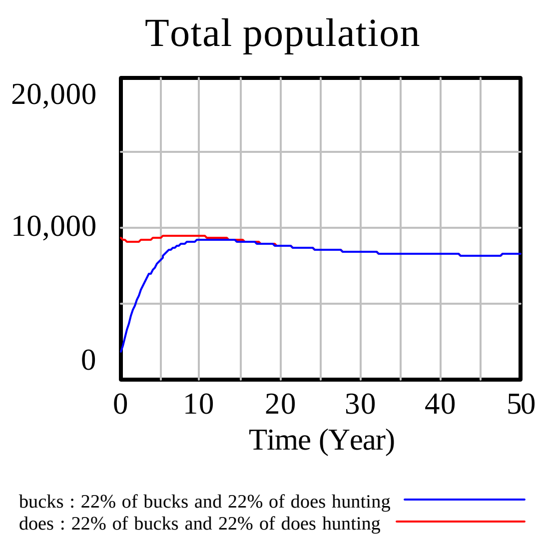


Figure 22. A 50-year deer population simulation with a 22% buck harvest and 22% does harvest.

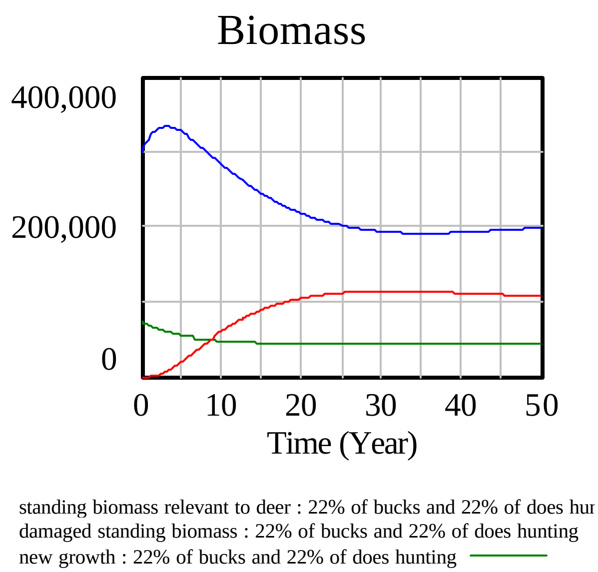


Figure 23. A 50-year forage biomass simulation with a 22% buck harvest and 22% does harvest.

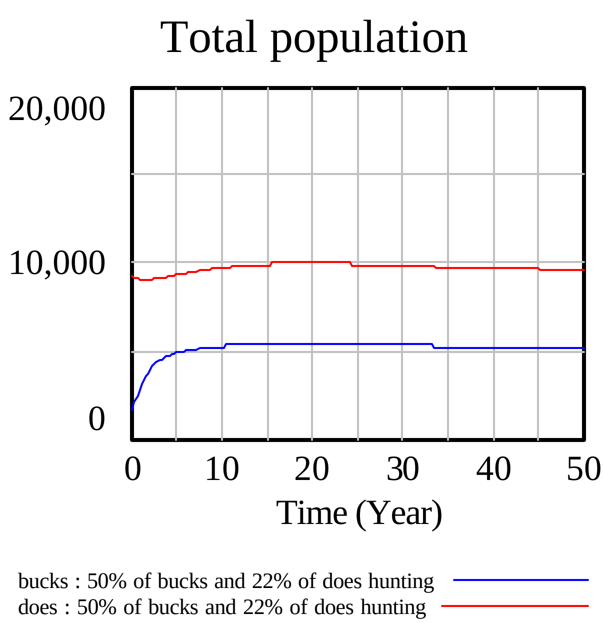


Figure 24. A 50-year deer population simulation with a 50% buck and 22% doe harvest.

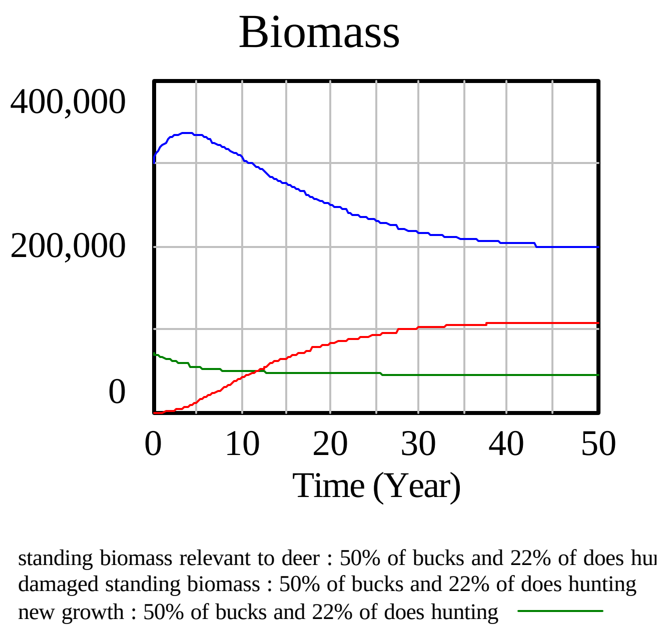


Figure 25. A 50-year forage biomass simulation with a 50% buck harvest and 22% doe harvest.

Table 1. Number of white-tailed deer predicted to be available in northestern Washington at the opening of the hunting season every 10 years with a 22% buck harvest and a 22% doe harvest.

Year	No. Bucks	No. Does
1	3645	9017
10	9081	9338
20	8760	8768
30	8354	8354
40	8187	8187
50	8182	8182

APPENDIX A.

Description of Technical Terms Used in System ModelAnalysis

Box Variable – Level: A pool of matters which has roles of accumulation and source.

Rate : Flows which come from or go to stocks to change their volumes

Variable – Auxiliary/Constant: Factors in model which control rates, convert and store equation or constant. No accumulating role

Reference Mode : A drawn graph of an important variable that changes over time of the dynamic problem as a target of the model

Slider: One of the modeling soft functions to vary parameters of variables to evaluate how the modeling results are going to change

APPENDIX C.

The Identification Number of the White-Tailed Deer Management Units and Management Areas in Northeastern Washington[1]

PMU11- GMU 101 (Ferry area)

PMU13- GMUs 105, 108, 111, 113, 117, 121, 124 (Pend Oreille, Spokane areas)

PMU14- GMUs 127, 130, 133 (Spokane area)

PMU15- GMUs 136, 139, 142 (Lincoln, Whitman areas)

PMU16- GMUs 145, 149, 154, 178, 181 (Walla Walla area)

PMU17- GMUs 162, 163, 166, 169, 172, 175, 186 (Whitman, Columbia, Garfield, Asotin areas)

[1] (Source: Washington Department of Fish and Wildlife, 2005)

APPENDIX C.

Equations Used in the *Vensim* System Model of White-Tailed Deer Populations in Northeastern Washington

(01) additional standing biomass= new growth-new forage consumption

(02) bio productivity= intrinsic bio productivity*productivity multiplier from damage*productivity multiplier from fullness

(03) birth= birth rate*does at the end of hunting season

(04) birth rate= normal birth with needs met*birth rate reduction due to doe reduced forage

(05) birth rate reduction due to doe reduced forage= lookup birth rate(equivalent fraction needs met)

(06) buck death due to hunting= buck hunting ratio*bucks

(07) buck hunting ratio= undefined

(08) bucks= INTEG (+fawns to bucks-buck death due to hunting-bucks natural death,1700)

(09) bucks natural death= bucks*natural death rate

(10) bucks ratio after hunting= bucks/total adult*10

(11) damaged biomass fraction= damaged standing biomass/max biomass

(12) damaged standing biomass= INTEG (+foraging on biomass causes damage-dying damaged biomass, 0)

(13) decay= decay rate*standing biomass relevant to deer

(14) decay rate= 0.1

(15) doe death due to hunting= doe hunting ratio*does

(16) doe hunting ratio= undefined

(17) does= INTEG (+fawns to does-doe death due to hunting-does natural death, 9200)

(18) does at the end of hunting season= does

(19) does natural death= does*natural death rate

(20) does ratio after hunting= does/total adult*100

(21) dying damaged biomass= damaged standing biomass*decay rate

(22) equivalent fraction needs met= MIN(1, new forage needs met+ fraction of old forage needs met*old biomass nutrition factor)

(23) fawn survival rate= 0.58

(24) fawns= INTEG (birth-fawns to bucks-fawns to does, 9100)

(25) fawns to bucks= fawns*fawn survival rate*sex ratio

(26) fawns to does= fawns*fawn survival rate*sex ratio

(27) FINAL TIME = 50

Units: Year

(28) forage required per deer per yr= 1MT

(29) foraging on biomass causes damage= fraction of old forage needs met*old forage required

(30) fraction of old forage needs met= MIN(1, old forage availability ratio)

(31) fraction of total harvest ratio= total harvest/total adult*100

(32) fullness fraction= (standing biomass relevant to deer + damaged standing biomass)/max biomass

(33) INITIAL TIME = 0

Units: Year

(34) intrinsic bio productivity=0.4

(35) lookup birth rate=

([(0,0) -(1,1)],(0,0),(0.1,0),(0.2,0.05),(0.3,0.1),(0.4,0.2),(0.5,0.4),(0.6,0.6),(0.7,0.9),(0.8,0.95),(0.9,0.98),(1,1))

(36) lookup natural death rate=

([(0,0) -(1,1)],(0,1),(0.1,1),(0. 2,1),(0.3,1),(0.4,0.67),(0.5,0.4),(0.6,0.25),(0.7,0.125),(0.8,0.11),(0.9,0.102),(1,0.1))

(37) lookup productivity multiplier from damage=

([(0,0) -(1,1)],(0,1),(0.2,1),(0.4,1),(0.6,0.9),(0.8,0.8),(1,0.8))

(38) lookup productivity multiplier from fullness=

([(0,0) -(1,1)],(0,1),(0.2,1),(0.4,0.9),(0.6,0.6),(0.8,0.2),(1,0))

(39) max biomass= 500000MT

(40) natural death rate=lookup natural death rate(equivalent fraction needs met)

(41) new forage availability ratio= new growth availability/total forage required

(42) new forage consumption= new forage needs met*total forage required

(43) new forage needs met= MIN(1, new forage availability ratio)

(44) new growth= bio productivity*standing biomass relevant to deer

(45) new growth availability= new growth*new growth within reach of deer

(46) new growth within reach of deer= 0.33

(47) normal birth with needs met= 0.68

(48) old biomass nutrition factor= 0.25

(49) old forage availability ratio= standing biomass available/MAX(1, old forage required)

(50) old forage required= total forage required-new forage consumption

(51) productivity multiplier from damage= lookup productivity multiplier from

damage(damaged biomass fraction)

(52) productivity multiplier from fullness= lookup productivity multiplier from fullness(fullness fraction)

(53) SAVEPER = TIME STEP

Units: Year

(54) sex ratio= 0.5

(55) standing biomass available= standing biomass within reach of deer*standing biomass relevant to deer

(56) standing biomass relevant to deer= INTEG (additional standing biomass-decay-foraging on biomass causes damage,300000)

(57) standing biomass within reach of deer= 0.33

(58) TIME STEP = 0.25

Units: Year

(59) total adult= bucks+ does

(60) total forage required= total population*forage required per deer per yr

(61) total harvest= buck death due to hunting+ doe death due to hunting

(62) total population= bucks+ does+ fawn